Driving Extreme Variability: Measuring the Variable Coronae of AGN

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Through detailed analysis of the reflection of the X-ray continuum in AGN from the accretion disc, it is possible to probe the innermost structures; the accretion flow itself and the X-ray emitting corona. Measuring the emissivity profile of the accretion disc, that is its pattern of illumination by the coronal X-ray source, and reverberation time lags between variability in the X-ray continuum and reflection, it is possible to determine the spatial extent of the X-ray emitting corona around the black hole.

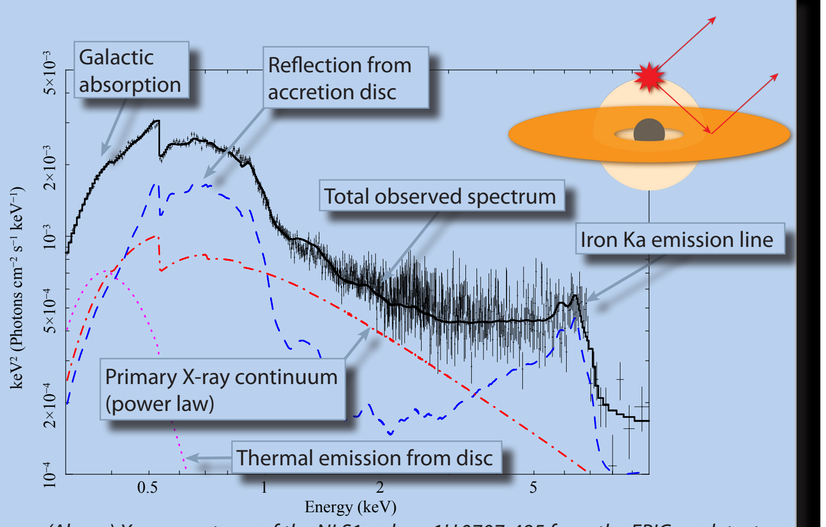
From detailed measurements of the corona from periods of high and low X-ray count rates from long observations of the narrow line Seyfert 1 galaxy, 1H0707-495, totalling more than 1.3 Ms with *XMM-Newton*, we see a corona that expands spatially as its luminosity increases, on short timescales. Using this insight gained from observations of 1H0707-495, similar measurements taken during the evolution of a prolonged X-ray flare of Markarian 335, observed with *Suzaku* in June 2013, trace the evolution of the corona during and after this event. When combined with the changing continuum spectrum, the evolving energetics of the corona are revealed, giving insight into the underlying accretion process.

Probing the Corona through X-ray Reflection

X-rays are thought to originate from a corona of energetic particles surrounding the central black hole of an AGN, produced by the inverse-Compton scattering of thermal seed photons originating from the accretion disc. As well as being observed directly, these X-rays may be reflected from the surface of the accretion disc. This causes a number of absorption and emission features to be imprinted on the spectrum of the X-rays that are reflected, the most promenent of which is the Kα emission line of iron, at 6.4keV (as measured in the rest frame of the emitting material).

The energies in an emission line originating from an accretion disc around a black hole will be shifted by relativistic effects due to the Doppler shifting of the emission as the material in the accretion disc orbits around the black hole as well as gravitational redshift of the emission from material closer to the central black hole. This causes the emission line to be broadened with an extended redshifted wing to lower energies originating from the innermost parts of the disc, as close as 1.235 r_g (GM/c^2), to rapidly spinning black holes.

The profile of a relativistically broadened emission line is different from successive radii in the disc, due to the change in the orbital velocity and gravitational redshift getting closer to the black hole. It is therefore possible to determine the emissivity profile of the accretion disc (the illumination pattern of the accretion disc by the corona) by fitting the relative contributions to the profile of the relativistically broadened iron Kα emission line of the blurred reflection spectrum from each radius (Wilkins & Fabian 2011). This emissivity profile will, in turn, depend upon the geometry and structure of the corona that illuinates the accretion disc. Thus, measurement of the emissivity profile allows us to probe the innermost structure of the accretion flow and corona, right down to the event horizon and innermost stable orbit.



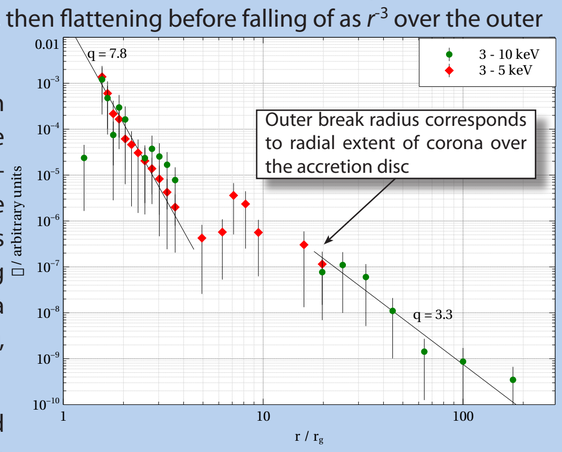
(Above) X-ray spectrum of the NLS1 galaxy 1H0707-495 from the EPIC pn detector on XMM-Newton interpreted as the reflection of X-rays from the accretion disc.

The Changing Corona of 1H0707-495

1H0707-495 is a narrow line Seyfert 1 (NLS1) galaxy, showing extremely variable X-ray emission from its nucleus. The X-ray spectrum above 1.1keV is well described by the combination of directly-observed continuum emission from the corona (a power law spectrum) and the relativistically blurred reflection of this emission by the accretion disc. The emissivity profile of the accretion disc in 1H0707-495 was found to be well described by a twice-broken power law, falling off steeply over the inner part of the disc, then flattening before falling of as r^{-3} over the outer regions of the disc (Wilkins & Fabian 2011).

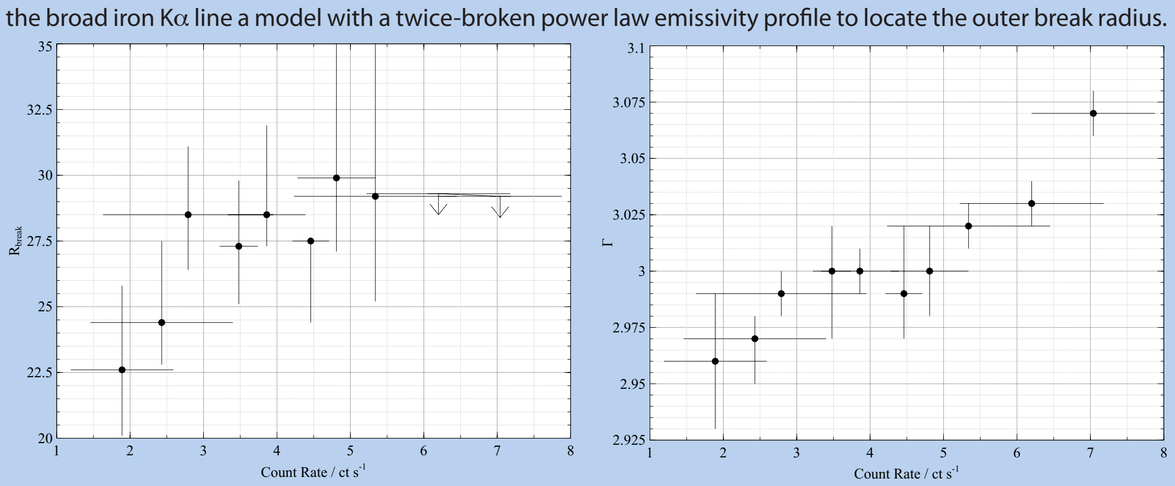
General relativistic ray tracing simulations of the illumination of the accretion disc by an extended corona show that the radius of the outer break point in the emissivity profile coincides with the radial extent of the corona over the plane of the disc, while measurments of reverberation time lags between variability in the continuum and corresponding variations in the reflected emission suggest that the corona is located vertically within 2 r_g of the disc (Zoghbi et al 2010, Wilkins & Fabian 2013).

The emissivity profile, combined with the measured reverberation time lags suggest a corona extended over the disc radially to around 30 r_g while extending vertically to just a few gravitational radii above the plane of the disc.



(Above) The emissivity profile of the accretion disc in 1H0707-495, measured by fitting radial contributions to the iron Kα line (Wilkins & Fabian 2011).

To determine how the corona changes as the X-ray count rate varies, average spectra were obtained from periods of varying count rate from a total of 1.3 Ms of observations with the EPIC pn detector on board *XMM-Newton*. The average extent of the corona at each count rate was inferred by maximum likelihood fitting to the profile of the broad iron Kα line a model with a twice-broken power law emissivity profile to locate the outer break radius.

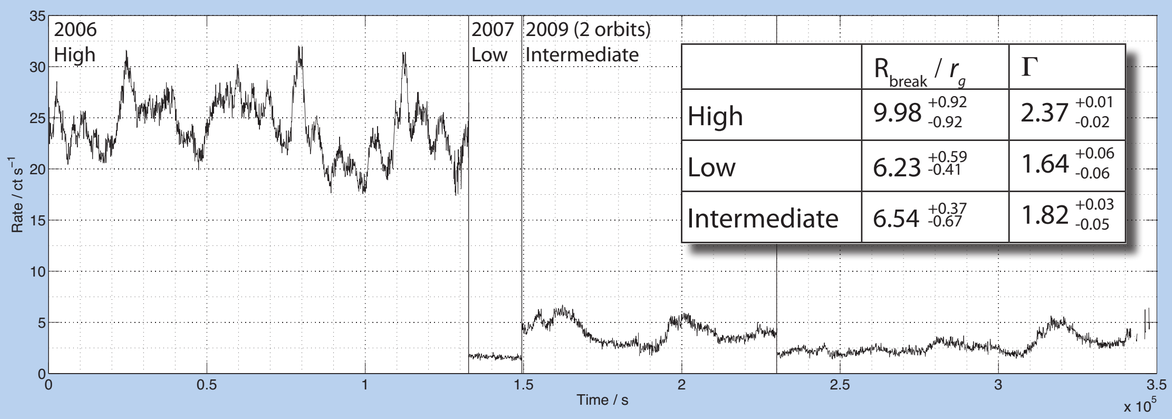


(Left) The outer break radius of the emissivity profile is found to increase with the X-ray luminosity of the corona, suggesting the corona is expanding over the accretion disc as it becomes brighter. (Right) The photon index (spectral slope) of the continuum is found to increase, with the spectrum becoming softer as the count rate increases.

Evolution of the Corona of Markarian 335

Markarian 335 is another NLS1 galaxy, though exhibiting much more extreme variability than 1H0707-495. Mrk 335 was observed four times with XMM Newton between 2006 and 2009 and was seen to vary between three distinct flux states, high (2006), low (2007) and intermediate (2009). Mrk 335 reveals a complicated spectrum, but showing a relativistically broadened iron Kα line reflected from the accretion disc (Gallo et al 2013).

The changes to the extent of the corona were measured using the above method, fitting a twice-broken power law to the emissivity profile of the broadened iron Kα line recorded with the EPIC pn detector, to spectra from each of the orbits to determine the long-timescale behaviour of the corona.

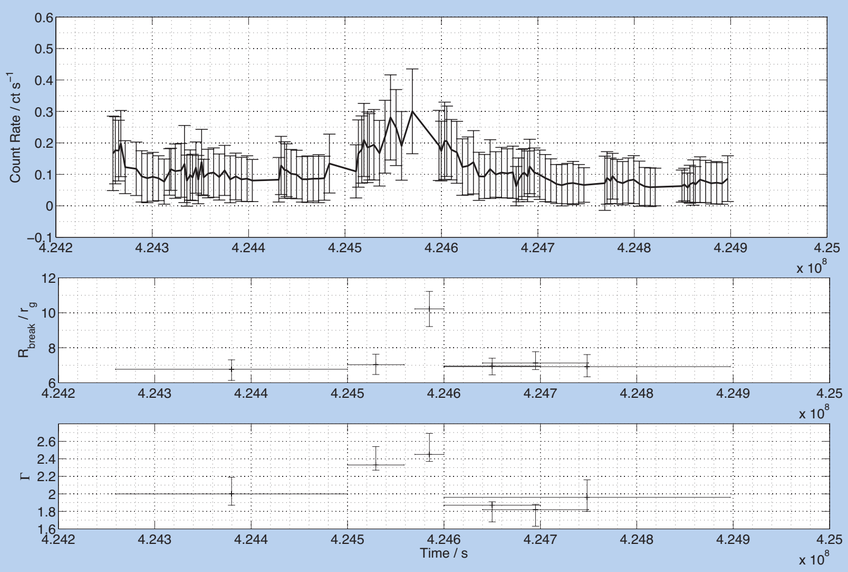


	R_{break} / r_g	Γ
High	$9.98^{+0.92}_{-0.92}$	$2.37^{+0.01}_{-0.02}$
Low	$6.23^{+0.59}_{-0.41}$	$1.64^{+0.06}_{-0.06}$
Intermediate	$6.54^{+0.37}_{-0.67}$	$1.82^{+0.03}_{-0.05}$

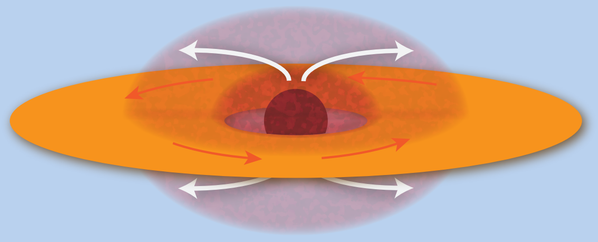
Mrk 335 Flare in Low Flux State *Suzaku* Observations

Markarian 335 was observed by *Suzaku* in 2013, to coincide with *NuSTAR* observations of this galaxy that find the source is in a low flux state, akin to the 2007 *XMM-Newton* observation and a spectrum well described by the relativistically blurred reflection of X-rays originating from a very compact corona (Parker et al 2014).

The Suzaku observations recorded a flare with the X-ray count rate doubling over around 15 hours. Fitting the emissivity profile of the accretion disc during successive time intervals reveals the evolution of the corona during this flare. The low background of the Suzaku XIS detector means that good quality spectra of the iron Kα line profile can be obtained from relatively short time intervals allowing the evolution of the corona to be followed during and after the flare.



Implications for the Corona



Identifying the outer break radius of the emissivity profile with the outermost radial extent of the X-ray emitting corona over the accretion disc suggests a corona that is expanding as its X-ray luminosity increases.

The softening of the continuum spectrum (increase in the spectral index, Γ) as the count rate increases shows that while the corona is expanding, the average energy density of the scattering particles throughout the corona is decreasing. In the context of Comptonisation of thermal seed photons, the average coronal temperature and/or the average optical depth encountered by the scattered photons decreases, though these changes need not be taking place wholesale throughout the whole corona.

The observations may point to an energetic central part of the corona that remains with the transient outer part being less dense and/or energetic. This is consistent with the observation that the the reflected flux rises only slightly as a weak function of the continuum flux with $R \sim C^{0.36}$ in 1H0707-495. Accounting for the change in gravitational light bending from an expanding corona, this shows that the number of photons produced, on average, per unit volume of the corona decreases as it expands, while the increase in total cross-section increases the total count rate of up-scattered continuum photons (Wilkins et al 2014).

Conclusions

The variation in the emissivity profile of the accretion disc, measured from the iron Kα line from periods of varying count rate suggests a corona that expands as its luminosity increases, giving rise to the extreme X-ray variability seen in AGN.

The observed softening of the continuum spectrum shows a decrease in either the average energy of the scattering particles making up the corona or the optical depth experienced by the up-scattered photons, consistent with there being structure within the corona.

Long X-ray observations of AGN through periods of high and low flux let us probe the innermost structure of the corona.

References

Wilkins D.R. & Fabian A.C., 2011, MNRAS 414, 1269-1277
Wilkins D.R. & Fabian A.C., 2012, MNRAS 424, 1284-1296
Wilkins D.R. & Fabian A.C., 2013, MNRAS 430, 247-258
Wilkins D.R. et al, 2014, in prep
Gallo L. et al, 2013, MNRAS 428, 1191-1200
Parker M.L. et al 2014, submitted to MNRAS
Zoghbi A. et al, 2010, MNRAS 401, 2419-2432

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